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THERMAL EXPANSION OF ALUMINUM AND VARIOUS IMPORTANT ALUMINUM ALLOYS

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ABSTRACT

This paper gives data on the linear thermal expansion of 4 samples of aluminum and 51 samples of important aluminum alloys. The preparation, chemical composition, heat treatment, etc., are included. Most of the specimens were examined from room temperature to about 500° C. Typical expansion curves of the various groups of samples are shown and discussed.

A description of the apparatus used in this research and a review of available information obtained by previous observers on the thermal expansion of aluminum and some of its alloys, are given.

The expansion of cast aluminum (99.95 per cent) from room temperature to 610° C. is represented by the following equation:

$$L_t = L_0\,[1+(22.58\,t+0.00989\,t^2)\,10^{-6}]$$

The relations between the chemical compositions and coefficients of expansion of aluminum-copper alloys (4 to 12 per cent copper) and aluminum-silicon alloys (4 to 12.5 per cent silicon), are shown in figures. The anomalous expansion of two aluminum-zinc alloys at constant temperature (about 270° C. on heating) is shown. From the results of previous observers and the present research, it is evident that the aluminum-zinc alloy of eutectoid composition (about 79 per cent zinc) shows the greatest change in expansion at the transformation or eutectoid temperature. A triangular diagram is shown which indicates the effect of change of composition on the coefficients of expansion of aluminum-silicon-copper alloys lying near the aluminum corner of the ternary system. The table in the summary gives a comparison of the average coefficients of expansion of the various groups of samples investigated.

CONTENTS

I. INTRODUCTION

The purpose of this paper is to give the results of an investigation on the linear thermal expansion of aluminum and various important aluminum alloys. Other physical properties have been determined during recent years by various investigators. Where lightness, strength, and durability are required these materials find wide application.

The coefficients of expansion of 4 samples of aluminum and 51 samples of important aluminum alloys were determined. The preparation, chemical composition, heat treatment, etc., are included. Most of the specimens were examined from room temperature to about 500° C. Typical expansion curves of the various groups of samples are shown and discussed. In some cases, the data on expansion are compared with the equilibrium diagrams of binary alloys.

A description of the apparatus used in this research and a review of available information obtained by previous investigators on the thermal expansion of aluminum and some of its alloys are given.

All samples and chemical analyses were furnished by the Aluminum Co. of America, New Kensington, Pa., except those noted otherwise in the text. The author wishes to express his appreciation for the cooperation by this company through J. D. Edwards, assistant director of research. Acknowledgement is also due to Dr. W. Souder and Dr. H. W. Gillett, Bureau of Standards, for valuable suggestions and to W. T. Sweeney, Bureau of Standards, for assistance in the investigation.

II. PREVIOUS DETERMINATIONS

In 1921, Souder and the present author presented data on the thermal expansion of two samples of aluminum (99.74 per cent). For information on these samples and a brief review of the results obtained by Dittenberger,[1] Henning,[2] and Jaeger and Scheel [3] on the thermal expansion of aluminum, the reader should refer to Scientific Paper of the Bureau of Standards, No. 426. Additional data by other observers are given in the following table:

[1] Dittenberger, Z. Ver. deutsch. Ing., **46**, p. 1532; 1902.
[2] Henning, Ann. d. Phys. (4), **22**, p. 631; 1907.
[3] Jaeger and Scheel, Elekt. Zeits., **40**, p. 150, Apr. 3, 1919.

TABLE 1.—Coefficients of Expansion of Aluminum

Observer	Date	Metal	Temperature or temperature range	Coefficient of expansion
			°C.	$\times 10^{-6}$
Calvert and Lowe [1]	1859	Aluminum (commercial)	0 to 100	22.2
Fizeau [2]	1869	Aluminum	40	23.13
Le Chatelier [3]	1889	....do	63	24.6
			600	31.5
Voigt [4]	1893	....do	30	23.06
Lussana [5]	1910	....do	27 to 126	[6] 23.94
			27 to 126	[7] 23.01
			27 to 126	[8] 22.17

[1] Calvert and Lowe, Proc. Roy. Soc. Lond., **10**, p. 315; 1859–1860.
[2] Fizeau, Compt. Rend., **68**, p. 1125; 1869; or Pogg. Ann. d. Phys. u. Chem., **138**, p. 26; 1869.
[3] Le Chatelier, Compt. Rend., **128**, p. 1444; and **108**, p. 1096; 1889.
[4] Voigt, Wied. Ann., **49**, p. 697; 1893.
[5] Lussana, Cim. (5), **19**, p. 182; 1910.
[6] At 1 atmosphere pressure.
[7] At 1,000 atmosphere pressure.
[8] At 2,000 atmosphere pressure.

The remainder of this section gives a review of the work on the thermal expansion of aluminum alloys.

In 1912, Le Chatelier [4] translated a Russian paper on the thermal expansion of annealed aluminum-zinc alloys by Smirnoff, who used the apparatus of Le Chatelier and Broniewski. The accompanying table and figure give the average coefficients of linear expansion between 25 and 250° C.

Table 2.—Coefficients of Expansion of Aluminum-Zinc Alloys (Smirnoff)

Zinc		Average coefficients of expansion between 25 and 250° C.
By weight	Atomic	
Per cent	Per cent	$\times 10^{-6}$
100.0	100.0	28.1
98.7	97.0	28.5
96.7	92.4	29.7
95.0	88.7	32.6
81.6	64.7	27.1
54.6	33.2	28.1
38.1	20.3	31.3
20.6	9.7	31.6
9.5	4.2	29.7
0.0	0.0	27.2

Smirnoff claims that his results agree with those obtained by thermal and micrographic analyses. The region of solid solutions of zinc in aluminum corresponds to the portion of the curve, *A B*, and point, *C*, represents what he believed to be the definite compound Al_2Zn_3. The maximum, *D*, corresponds to a eutectic mixture and not to a solid solution. At 260 to 270° C., he found

[4] Le Chatelier, Comptes Rendus, **155**, p. 351; 1912.

abrupt changes in the dimensions of alloys containing (as he believed) crystals of Al_2Zn_3. He states that this phenomenon indicates the existence of a transformation of the crystals of the definite compound, which is accompanied by a linear change of 0.26 per cent in the dimensions. The curve, *L M N*, in the

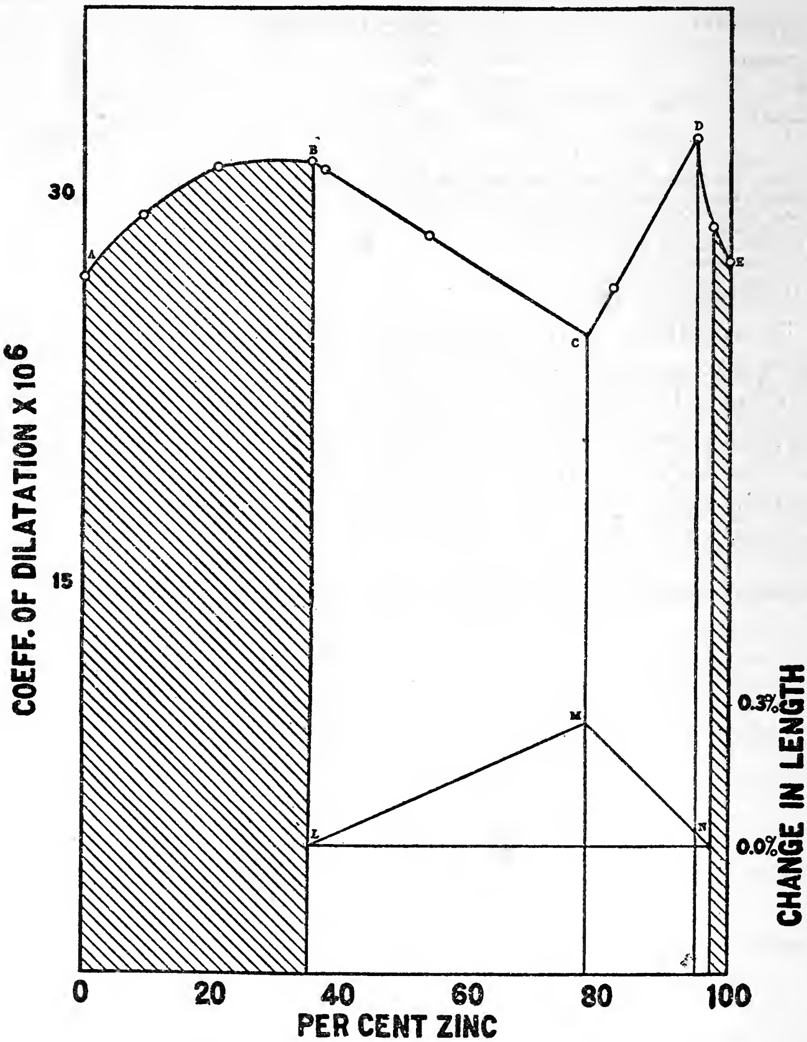

FIG. 1.—*Average coefficients of expansion of aluminum-zinc alloys from 25 to 250° C., and the changes in length at the transformation temperature, 260 to 270° C. (Smirnoff)*

preceding figure shows the changes in length at the transformation temperature for various alloys. He states that the maximum, *M*, corresponds to the definite compound Al_2Zn_3, and that the ordinates vary in proportion to the quantity of crystals contained in the alloy.

In 1917, Shakespear[5] made and described some expansion tests on aluminum and several of its alloys between room temperature and 300° C., as follows:

> In each case the temperature was raised from room temperature to about 260° C., the expansion being noted at intervals. The specimen was then kept for some hours at about 260° C., the extension being observed at intervals until no further elongation took place. A second heating was given, but in most cases this produced no further sensible permanent change.
>
> The general effects are of the same type in all cases, but absolute values both of coefficient of expansion and of permanent change are not necessarily the same even for different parts of the same casting. Apparently the rate of cooling of the casting has a marked effect, and different parts of the casting, in general, cool at different rates.

The samples examined were cut from 100 mm R. A. F. type pistons. Several representative curves show the growth at about 260° C. and the marked deviation between the expansion curves on heating and on cooling.

Expansion data obtained by Shakespear are given in Table 3. In cases where two samples were taken from the same casting, A denotes sample from side of casting and B sample from crown. He states that the expansion was observed in terms of its excess over that of copper, and that the coefficients of linear expansion are given on the assumption that the mean value of coefficient for copper for the range 100 to 200° C. is 20.0×10^{-6} per degree centigrade. Since the average coefficient of expansion of pure copper was recently[6] found to be 17.6×10^{-6} per degree centigrade between 100 and 200° C., the coefficients given in this table should be decreased by $(20.0-17.6)\ 10^{-6}$ or 2.4×10^{-6}. For example, the coefficient of expansion of aluminum, therefore, becomes $(27.1-2.4)\ 10^{-6}$ or 24.7×10^{-6} per degree centigrade between 100 and 200° C.

Table 3.—Expansion Data on Aluminum and Several Aluminum Alloys (Shakespear)

Number [a]	Approximate chemical composition					Mean coefficient of expansion 100 to 200° C.		Permanent extension in millionths of original length	Time required for annealing
	Al	Cu	Mn	Sn	Zn	First heating	Second heating		
						$\times 10^{-6}$	$\times 10^{-6}$		
0	85	14	1			27.0	26.5	960	5 hours at 254° C.
2 A	85	14	1			25.8	25.4	500	
2 B	85	14	1			24.9	25.6	595	6 hours at 280° C.
4	88	12				26.6	26.4	580	5 hours at 260° C.
5	99.5					27.1	27.1		
1 A	84	14	1	1		25.0	25.9	400	
1 B	84	14	1	1		26.1	25.9	730	Do.
3 A	83	14	1	1	1	28.6	25.6	550	
3 B	83	14	1	1	1	26.0	26.1	686	4 hours at 260° C.

[a] Number 0 from piston made by Mills (sand cast); number 5 from Brit. Aluminium Co.; and the remainder from pistons made in chills or "dies" by Birmingham Aluminium Castings Co.

[5] Shakespear, "Reports of the Light Alloys Subcommittee" (Advisory Committee for Aeronautics, London), p. 48, June, 1921.

[6] B. S. Sci. Paper No. 410.

In 1921 Schulze[7] investigated the thermal expansion of aluminum, zinc, and seven aluminum-zinc alloys (12.5, 25, 37.5, 50, 62.5, 75, and 87.5 per cent Al). Observations were taken at room temperature in a water bath, at 100° C. in steam, at 200° C. in methyl benzoate vapor, and at higher temperatures in an electrically heated saltpeter bath. Before the expansion tests three of the samples (100, 87.5, and 75 per cent Al) were heated to 420° C. and the other specimens to 320° C.

The following table gives average coefficients of expansion which were computed from Schulze's data. He states that his results have an accuracy of approximately 1 per cent.

TABLE 4.—Coefficients of Expansion of Aluminum-Zinc Alloys (Schulze)

Chemical composition		Average coefficients of expansion				
Zn	Al	20 to 100° C.	20 to 200° C.	20 to 250° C.	20 to 300° C.	20 to 400° C.
Per cent	Per cent	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$
0	100	23.6	24.5	....	25.2	25.9
12.5	87.5	23.9	24.8	....	25.9	27.1
25	75	26.1	27.1	27.7	28.0	29.1
37.5	62.5	26.6	27.4	28.9	30.4	....
50	50	26.5	27.6	29.3	....	....
62.5	37.5	26.1	27.4	29.8	....	....
75	25	27.1	28.5	30.4	....	....
87.5	12.5	26.4	29.1	30.7	....	....
100	0	36.4	37.6	38.2	38.6	....

Schulze states that his values for the expansion of zinc are extraordinarily high; for example, the average coefficient of expansion between 20 and 100° C. is 36.4×10^{-6}. For commercial zinc, which showed thermal after effects, he previously found the coefficient to be 30×10^{-6} for the same temperature range.

The expansion curves of zinc, aluminum, and the alloys containing 87.5 and 75 per cent Al, respectively, can be represented by quadratic equations. The expansion curves of the other alloys investigated are complicated, as may be seen from the accompanying figure. For the alloys containing 62.5, 50, 37.5, 25, and 12.5 per cent Al, respectively, transformations were observed between 250 and 280° C. A sudden expansion occurs with increasing temperature, and a similar contraction with decreasing temperature. The largest hysteresis loops were observed in the alloy containing 28 per cent Al. He claims that separate tests

[7] Schulze, Phys. Zeit., 22, p. 403; 1921.

showed that these retardation phenomena are independent of the time.

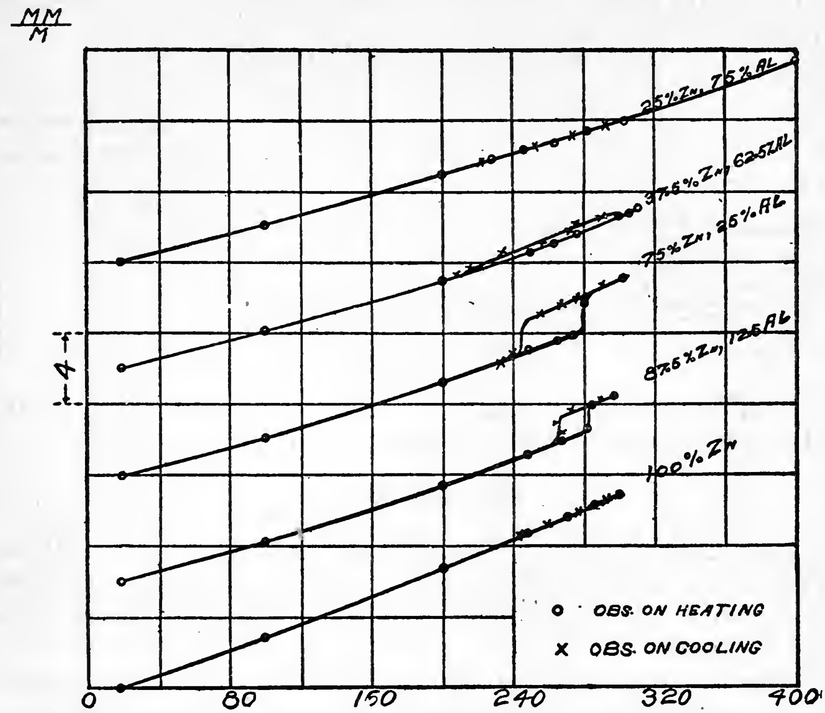

FIG. 2.—*Thermal expansion of some aluminum-zinc alloys.* (*Schulze*)

A summary of the results of other investigations on aluminum alloys is given in Table 5, the last table of this section.

TABLE 5.—Coefficients of Expansion of Some Aluminum Alloys

Observer	Date	Alloy	Temperature or temperature range	Coefficient of expansion
			° C.	$\times 10^{-6}$
Le Chatelier[1]	1889	100 Cu, 0 Al	63	16.4
		91 Cu, 9 Al	63	16.3
		75 Cu, 25 Al	63	16.5
		60 Cu, 40 Al	63	15.7
		50 Cu, 50 Al	63	15.8
		33 Cu, 67 Al	63	16.2
		30 Cu, 70 Al	63	20
		18 Cu, 82 Al	63	21.9
		0 Cu, 100 Al	63	24.6
Stadthagen[2]	1901	Magnalium[3]	12 to 39	23.8
Disch[4]	1921	Electron metal[5]	0 to 100	28.4
			0 to 200	28.6
			0 to 300	28.7

[1] Le Chatelier, Compt. Rend., 128, p. 1444; 1889.
[2] Stadthagen, Deutsche Mech.-Ztg., p. 21; 1901.
[3] Al 85.89, Mg 12.71, Si 0.71, Fe 0.46, Cu 0.08 per cent. (Density 2.538.)
[4] Disch, Zeits. f. Physik, 5, 173; 1921.
[5] Coefficients of expansion computed from data by Disch.

III. MATERIALS INVESTIGATED

The samples investigated are grouped into eight series as given in Table 6.

TABLE 6.—Classification of Materials

Series	Aluminum content	Number of samples
	Per cent	
1. Aluminum (a) Pure aluminum	99.95	2
1. Aluminum (b) Commercial aluminum	99.15	2
2. Aluminum-copper alloys	87 to 95	12
3. Aluminum-silicon alloys	87 to 95	7
4. Aluminum-zinc alloys	5 to 86	4
5. Aluminum-manganese and aluminum-manganese-copper alloys	96 to 98	6
6. Aluminum-silicon-copper and aluminum-silicon-copper-manganese alloys	84 to 94	12
7. Duralumin	94 to 95	8
8. Verilite	95.5	2

Other details (preparation, chemical composition, heat treatment, etc.) relating to these specimens will be given later.

IV. APPARATUS

Figure 3 shows part of the apparatus used in this investigation. With this equipment it is possible to determine the linear thermal expansion of solids for various temperature ranges between −150 and +1,000° C.

Temperatures were determined by means of thermocouples and a potentiometer, and length changes with the movable comparator (shown on track) consisting of two microscopes rigidly clamped on an invar bar at a distance from each other equal to the length of the specimen (30 cm). The microscopes were so arranged that they could first be sighted on a reference bar (near center of figure) and then on observation wires which were in contact with the ends of the specimen.

The two furnaces at the left are electrically heated air furnaces. The white furnace can be heated from room temperature to 1,000° C., and the black furnace from room temperature to 700° C.

The apparatus at the extreme right is a return-flow bath that may be filled with oil, gasoline, or pentane. The liquid used depends on the temperature desired. Electric resistance coils surrounded by, and in contact with, the liquid are used for heating. Cooling below room temperature is effected by the expansion of compressed air within a coil of copper tubing immersed in the bath containing gasoline or pentane. The liquid surrounding the specimen is kept in circulation by means of a propeller. With this return-flow bath it is possible to make measurements at any temperature between −150 and +300° C.

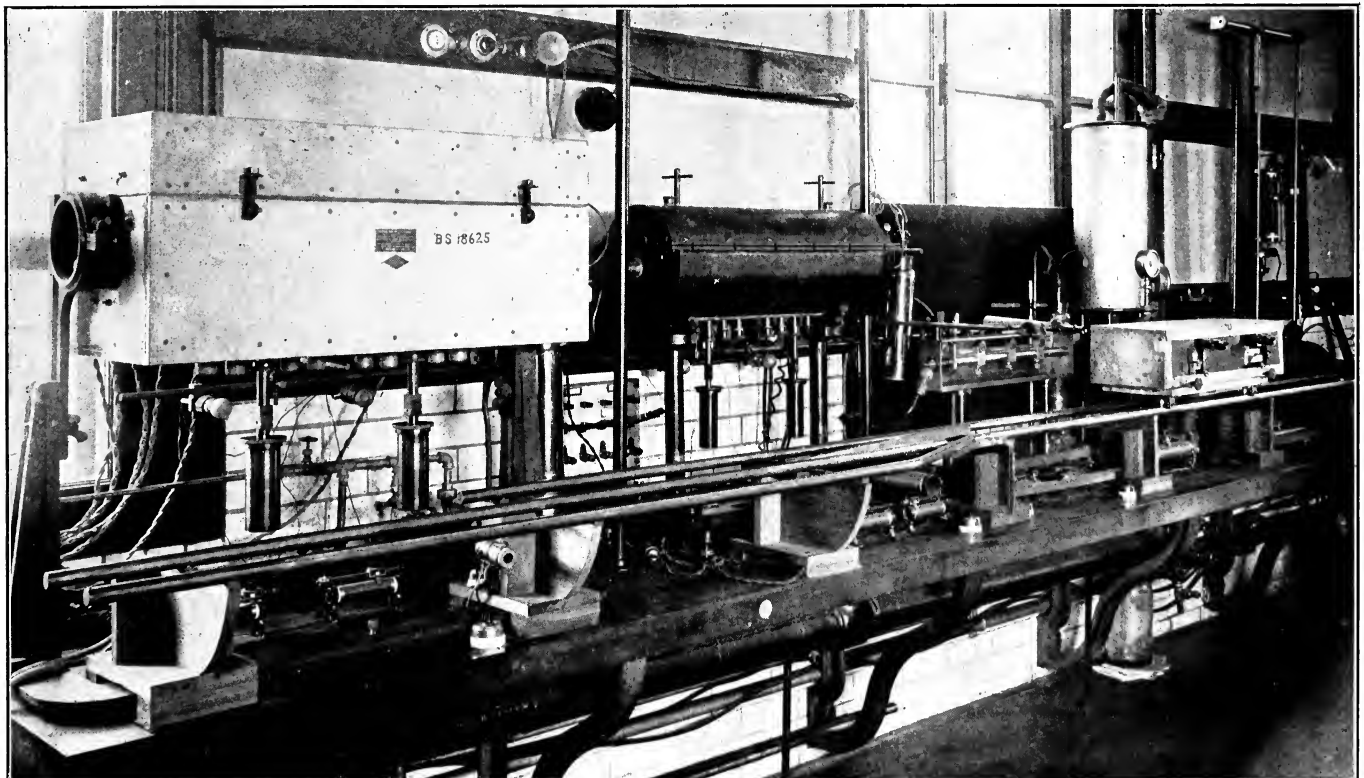

FIG. 3.—*Part of expansion apparatus*

For additional information about the apparatus and methods used in making determinations of thermal expansion reference should be made to Scientific Papers of the Bureau of Standards Nos. 219, 352, and 410.

V. RESULTS

The 55 samples investigated were divided into eight series as indicated in the table of contents. In all cases the coefficients of expansion were derived from the observations on heating.

1. ALUMINUM (SERIES 1)

In this series there are two samples of exceptionally pure aluminum and two samples of commercial aluminum.

(a) PURE ALUMINUM

The two samples of pure aluminum were cut from a bar of aluminum cast in a graphite mold. They received no additional treatment before the expansion tests. The chemical analysis of samples taken from the ends of the bar was as follows:

	Per cent
Silicon	0.014
Iron	.015
Copper	.019
Aluminum (by difference)	99.952

The density [8] of a sample cut from this bar was found to be 2.680 g/cc³ at 20° C.

One sample was examined from 22 to 618° C. and the other from 20 to 609° C. The observations are shown graphically in Figure 4. The results obtained on heating may be represented by the following empirical equations derived by the method of least squares: For sample S821

$$\Delta L = 23.12\ (t - 22.4)10^{-6} + 0.00965\ (t - 22.4)^2 10^{-6}$$

and for sample S828

$$\Delta L = 22.88\ (t - 20.3)10^{-6} + 0.01013\ (t - 20.3)^2 10^{-6}$$

In the first equation ΔL represents the expansion or change in length from 22.4° C. to any temperature t between 22.4 and 618° C., and in the second equation ΔL represents the expansion from 20.3° C. to any temperature t between 20.3 and 609° C. The probable error of ΔL is ± 0.000026 for S821 and ± 0.000020 for S828.

[8] Determined by E. L. Peffer, of this bureau.

The equations given may be transformed as follows: For sample S821

$$L_t = L_0[1 + (22.69\, t + 0.00965\, t^2)10^{-6}] \tag{1}$$

and for sample S828

$$L_t = L_0[1 + (22.47\, t + 0.01013\, t^2)10^{-6}] \tag{2}$$

where L_t represents the length of the metal at any temperature t within the proper temperature limits and L_0 the length at 0° C.

The following average equation

$$L_t = L_0[1 + (22.58\, t + 0.00989\, t^2)10^{-6}] \tag{3}$$

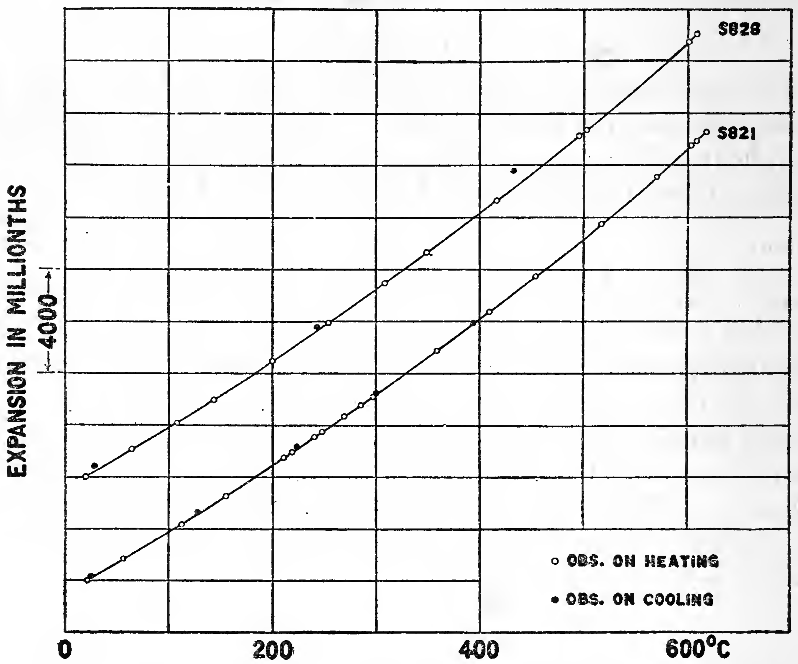

FIG. 4.—*Linear expansion of two samples of pure aluminum (99.95 per cent)*

may be given as the most probable second degree equation for the expansion of cast aluminum (99.95 per cent) from room temperature to about 610° C. The length determined from this equation, at any temperature t, is accurate to ±0.00002 per unit length.

The average coefficients of expansion for various temperature ranges given in Table 7 were computed from equations (1), (2), and (3).

TABLE 7.—Average Coefficients of Expansion of Aluminum

Temperature range (in degrees centigrade)	Average coefficients of expansion per degree centigrade		
	Sample S821	Sample S828	Average [1]
	$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$
20 to 100	23.8	23.7	23.8
100 to 200	25.6	25.5	25.5
200 to 300	27.5	27.5	27.5
300 to 400	29.4	29.6	29.5
400 to 500	31.4	31.6	31.5
500 to 600	33.3	33.6	33.5
300 to 600	31.4	31.6	31.5
20 to 200	24.8	24.7	24.7
20 to 250	25.3	25.2	25.2
20 to 300	25.8	25.7	25.7
20 to 400	26.7	26.7	26.7
20 to 500	27.7	27.7	27.7
20 to 600	28.7	28.8	28.7

[1] Coefficients given in the last column were computed from equation (3).

The average coefficients of the two samples of aluminum agree fairly well. The largest variation in the coefficients is 0.3×10^{-6}. The observations on cooling are generally slightly above the heating curves, as may be seen from Figure 4. At the end of the expansion tests, S821 was about 0.01 per cent longer than before the test and S828 was about 0.02 per cent longer.

(b) COMMERCIAL ALUMINUM

Expansion determinations from room temperature to about 600° C. were also made on two duplicate samples (S843 and S844) cut from commercially pure aluminum sheets, rolled to one-fourth inch. The composition of these specimens was as follows:

	Per cent
Silicon	0.32
Iron	.36
Copper	.10
Manganese	.07
Aluminum (by difference)	99.15

The hardness number was found to be 45 (Brinell). The Aluminum Co. of America states that practically all of the rolled commercially pure aluminum sheet used in the United States consists of aluminum similar to S843 and S844.

The observations obtained on the two samples of commercial aluminum are shown graphically in Figure 5. Both expansion curves are regular. At the end of the test sample S844 was found to be about 0.01 per cent longer than before the test. The length of the other specimen was practically the same before and after the test.

Table 8 gives average coefficients of expansion which were computed from the expansion curves.

TABLE 8.—Average Coefficients of Expansion of Commercial Aluminum

Temperature range (in degrees centigrade)	Average coefficients of expansion per degree centigrade	
	Sample S843	Sample S844
	$\times 10^{-6}$	$\times 10^{-6}$
20 to 100	23.9	24.0
20 to 200	26.1	25.7
20 to 250	26.6	26.4
20 to 300	26.8	26.6
20 to 400	27.3	27.0
20 to 500	28.0	27.8
20 to 600	28.7	28.6

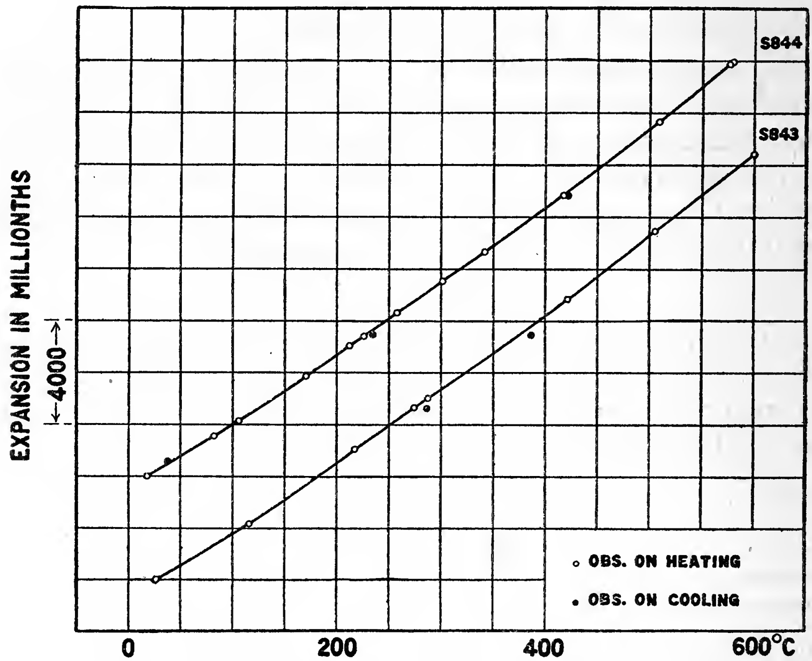

FIG. 5.—*Linear expansion of two samples of commercial aluminum (99.15 per cent)*

The mean variation in the coefficients of expansion of the two samples of commercial aluminum is 0.2×10^{-6}. For nearly all temperature ranges, the coefficients of expansion of the two samples of commercial aluminum are larger than the corresponding coefficients of the two samples of pure aluminum (see Tables 7 and 8).

2. ALUMINUM-COPPER ALLOYS (SERIES 2)

Series 2 includes 12 samples of cast aluminum-copper alloys containing from 3.8 to 11.9 per cent copper. The chemical analyses of the castings are given in Table 9.

TABLE 9.—Chemical Analyses of Aluminum-Copper Alloys

Laboratory number	Material	Chemical analysis: Aluminum[1]	Copper	Silicon	Iron	Manganese
		Per cent	Per cent	Per cent	Per cent	Per cent
S833	Approximately 4 per cent copper alloy, sand cast	95.41	3.75	0.30	0.36	0.18
S834	Cut from same bar as S833					
S967	Approximately 6 per cent copper alloy, cast in green sand	93.41	5.81	.36	.42	....
S968	Cut from same bar as S967					
S829[2]	Approximately 8 per cent copper alloy, cast in green sand	91.14	7.68	.39	.46	.33
S830	Cut from same bar as S829					
S831[2]	Approximately 8 per cent copper alloy, cast in green sand, different melt	91.13	7.87	.33	.45	.22
S832	Cut from same rod as S831					
S969	Approximately 10 per cent copper alloy, cast in green sand	89.22	9.95	.39	.44	....
S970	Cut from same bar as S969					
S971	Approximately 12 per cent copper alloy, cast in green sand	87.30	11.88	.39	.43	....
S972	Cut from same bar as S971					

[1] Per cent aluminum determined by difference.
[2] This composition for No. 12 alloy, the most widely used casting alloy of aluminum in the United States, meets S. A. E. specification No. 30. These percentages of Si, Fe, and Mn are permissible, but not required.

Expansion tests were made from room temperature to about 500° C. on all samples except three (S834, S829, and S832), which were heated to only 300° C. Samples S834 and S832 were tested in an oil bath. The remaining 10 samples were tested in electrically heated air furnaces.

Figure 6 shows representative expansion curves of three aluminum-copper alloys containing approximately 4, 8, and 12 per cent copper, respectively. The expansion curves of all samples heated to 500° C. showed irregularities at about 300° C. These irregularities are doubtless due to the taking up of $CuAl_2$ into solid solution, or to the homogenizing of a cored solid solution.

The cooling curves of all samples heated to 500° C. intersect the heating curves. The maximum deviation between the heating and cooling curves is about 1,100 millionths per unit length. At the end of the expansion tests the specimens were longer than before these tests. After annealing aluminum-copper alloys about five hours at 260° C. Shakespear found that, in most cases, heating to this temperature again caused no further permanent change in length.

From the expansion curves of the 12 alloys, the average coefficients of expansion given in Table 10 were computed for various

temperature ranges. This table also gives the changes in length from the original lengths after the thermal expansion tests. The plus (+) sign indicates an increase in length.

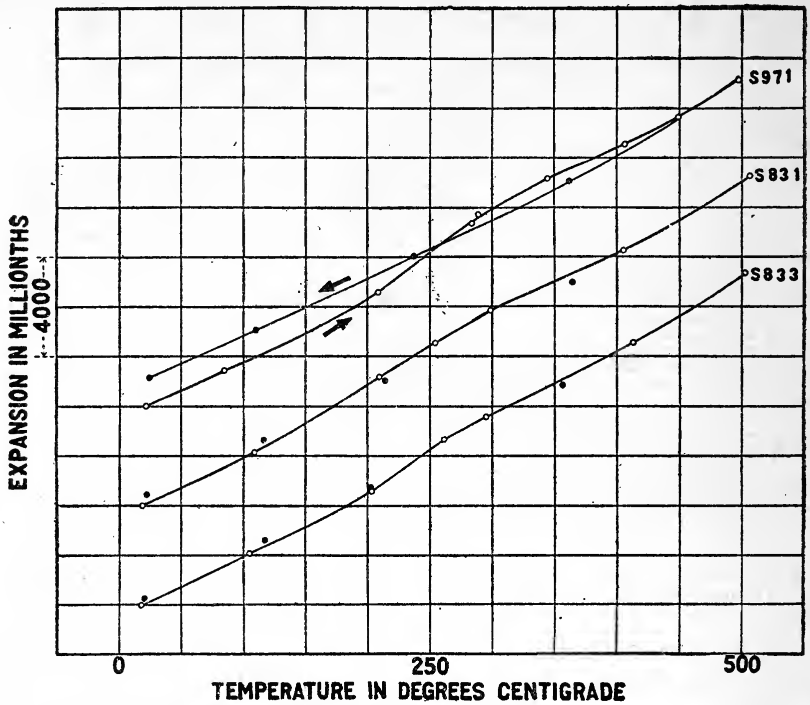

FIG. 6.—*Linear expansion of three aluminum copper alloys (approximately 4, 8, and 12 per cent copper, respectively)*

TABLE 10.—Average Coefficients of Expansion and Length Changes of Aluminum-Copper Alloys

Laboratory number	Material	Average coefficients of expansion per degree centigrade: 20 to 100° C.	20 to 200° C.	20 to 250° C.	20 to 300° C.	20 to 400° C.	20 to 500° C.	Change in length due to heat treatment received during test
		$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	Per cent
S833	Approximately 4 per cent copper alloy, sand cast	23.7	24.6	27.0	27.2	26.7	27.5	+0.02
S834	Cut from same bar as S833	22.7	24.4	25.4	26.4	....	....	+.04
S967	Approximately 6 per cent copper alloy, cast in green sand	23.8	24.9	26.5	27.8	27.8	28.0	+[1].07
S968	Cut from same bar as S967	23.2	25.2	28.1	29.2	28.0	28.5	+[1].09
S829	Approximately 8 per cent copper alloy, cast in green sand	24.6	25.3	26.1	27.1	....	....	....
S830	Cut from same bar as S829	23.7	26.3	27.8	28.0	26.6	27.4	+.05
S831	Approximately 8 per cent copper alloy, cast in green sand, different melt	23.4	26.8	27.7	28.0	26.6	27.2	+[1].04
S832	Cut from same rod as S831	23.4	24.6	26.4	27.4	....	....	+[1].08
S969	Approximately 10 per cent copper alloy, cast in green sand	22.4	24.2	26.1	28.3	27.3	27.7	+[1].11
S970	Cut from same bar as S969	22.4	....	27.8	27.8	26.7	27.0	+[1].07
S971	Approximately 12 per cent copper alloy, cast in green sand	22.4	24.1	26.8	28.6	27.5	27.6	+[1].11
S972	Cut from same bar as S971	22.2	23.6	28.5	28.6	26.8	27.0	+.07

[1] At any given temperature above room temperature the variation between the expansion curves on heating and cooling did not exceed this value.

Differences were found in the coefficients of expansion of some samples cut from the same bars. These variations indicate that the original bars were probably not homogeneous. Shakespear, as noted previously, also found variations in the coefficients of expansion of different parts of aluminum-copper castings. The average coefficients of expansion of the 12 alloys vary from 22.2×10^{-6} to 24.6×10^{-6} per degree centigrade between 20 and 100° C. For the range from 20 to 300° C., the coefficients vary from 26.4×10^{-6} to 29.2×10^{-6} per degree centigrade.

Figure 7 shows the relations between the composition (per cent copper) of the aluminum-copper alloys and the average coefficients

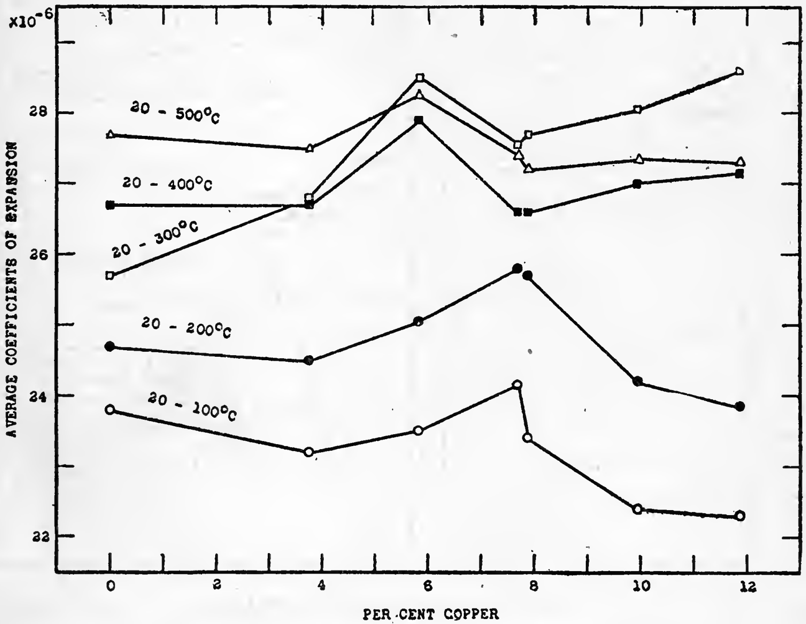

FIG. 7.—*Relations between the copper content and the coefficients of expansion of aluminum-copper alloys*

of expansion for various temperature ranges. In most cases each plotted value represents an average of two samples cut from the same bar of alloy. The values for 0 per cent copper (or 100 per cent aluminum) were taken from Table 7 of series 1. The curves indicate maxima at about 6 or 8 per cent copper.

For a comparison of the constitution of the aluminum-copper alloys and the coefficients of expansion given in the preceding figure, the reader should also refer to Figure 8, which shows the aluminum end of the aluminum-copper equilibrium diagram. The solubility curve, *b e*, was determined by Merica, Waltenberg,

and Freeman,[9] and the remainder of the diagram was taken from the results of previous investigators. Merica and his associates state that the solubility of $CuAl_2$ decreases with decreasing temperatures from about 4 per cent at 525° C. to about 1 per cent at 300° C., and is apparently still diminishing at lower temperatures.

Carpenter and Edwards[10] found that aluminum-rich alloys containing from 0 to about 5 per cent copper consist of solid solutions of copper in aluminum, and alloys containing from 5 to about 33 per cent copper consist of solid solutions with a eutectic which contains about 67 per cent aluminum and melts at about

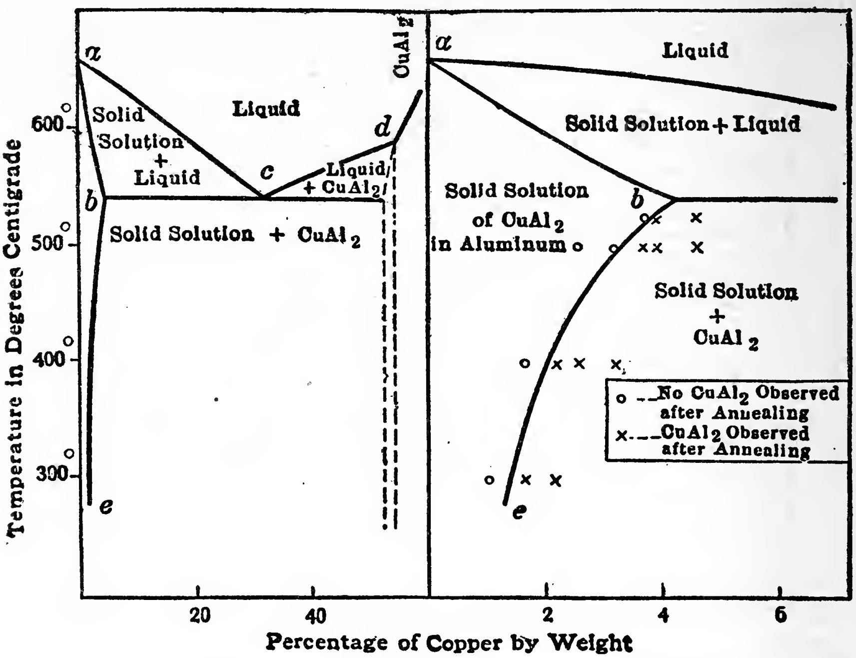

FIG. 8.—*The aluminum end of the aluminum-copper equilibrium diagram*

540° C. Rosenhain, Archbutt, and Hanson[11] state that approximately 5 per cent of copper is soluble in solid aluminum at 540° C., and that this amount decreases to about 3 per cent at 200° C.

3. ALUMINUM-SILICON ALLOYS (SERIES 3)

Series 3 includes seven samples of aluminum-silicon alloys containing from 4 to 12.5 per cent silicon. The chemical analyses of these alloys are given in Table 11.

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[9] Merica, Waltenberg, and Freeman, B. S. Sci. Paper No. 337.

[10] Carpenter and Edwards, Eighth Report to Alloys Research Committee, Proc. Inst. Mech. Eng., London, p. 57; 1907.

[11] Rosenhain, Archbutt, and Hanson, Eleventh Report to the Alloys Research Committee.

TABLE 11.—Chemical Analyses of Aluminum-Silicon Alloys

Laboratory number	Material	Chemical analysis			
		Aluminum [1]	Silicon	Iron	Copper
		Per cent	Per cent	Per cent	Per cent
S866 [2]	4 per cent silicon alloy	95.00	4.15	0.52	0.33
S871 [2]	7 per cent silicon alloy	91.98	7.28	.47	.27
S868 [2]	10 per cent silicon alloy	89.47	9.81	.50	.22
S939	12.5 per cent silicon alloy cast in green sand	86.81	12.55	.56	.08
S940	Cut from same bar as S939				
S941	Modified 12.5 per cent silicon alloy	Same as S939 except that it has had 0.1 per cent metallic sodium [3] added to the molten metal just before casting.			
S942	Cut from same bar as S941				

[1] Aluminum by difference.
[2] Submitted by the engineering division, Air Service of the War Department, McCook Field, Dayton, Ohio. (Chemical analysis by Aluminum Co. of America.)
[3] This is according to the process described in U. S. Patent 1410461. J. D. Edwards, of the Aluminum Co. of America, states that this treatment results in giving the silicon particles a very high degree of dispersion. He also says that sample S939 (normal alloy) will show a rather coarse fracture, but sample S941 (modified alloy) will show a very fine fracture very much like that of steel.

Samples S866, S871, and S868 were sand cast. Before the expansion tests, these specimens were heated to 400° C. and allowed to cool in the furnace. Expansion tests were then made on these samples from room temperature to 300° C. in an oil bath. Samples S939 to S942, inclusive, were tested in an electrically-heated air furnace, from room temperature to about 530° C. Tests were repeated on S939 and S940. In most cases (except the normal 12.5 per cent silicon alloys S939 and S940), the observations obtained on cooling lie near the expansion curves obtained on heating.

Figure 9 shows the expansion curves of three aluminum-silicon alloys containing 4, 7, and 10 per cent silicon, respectively. The expansion curves of these alloys are regular.

Figure 10 shows the expansion curves of a normal 12.5 per cent silicon alloy (S939) and a modified[12] 12.5 per cent silicon alloy (S941). In the first tests, the expansion curves of the two normal alloys (S939 and S940) show a marked change in the rate of expansion at about 250° C., and the curves obtained on cooling deviate from the curves on heating, between 300° C. and room temperature. At the end of these tests, the samples were decidedly longer than before the tests. On reheating these samples in the second tests, the expansion curves lie perceptibly above the curves obtained in the first tests, but do not indicate marked changes in the rate of expansion. The curves on cooling in the second tests again show a deviation from the curves on heating, between 300° C. and room temperature, but to a much smaller degree. The

[12] For definition and preparation, see J. D. Edwards, Chem. and Met. Eng., 27, p. 654; 1922.

expansion curves of the two modified specimens do not show the phenomena obtained in the normal samples.

The average coefficients of expansion computed from the expansion curves on heating, are given in Table 12. This table

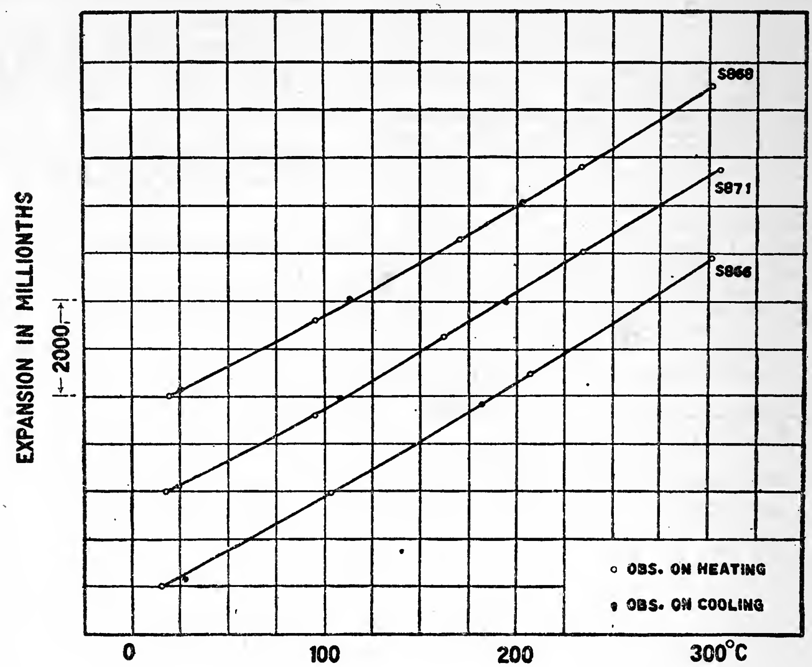

FIG. 9.—*Linear expansion of three aluminum-silicon alloys (4, 7, and 10 per cent silicon, respectively)*

also indicates the changes in length after the expansion tests from the lengths before these tests. The plus (+) sign signifies an increase in length, and the minus (−) sign a decrease in length.

TABLE 12.—Average Coefficients of Expansion and Length Changes of Aluminum-Silicon Alloys

Laboratory number	Material	Average coefficients of expansion per degree centigrade						Changes in length due to heat treatment received during test
		20 to 100° C.	20 to 200° C.	20 to 300° C.	20 to 400° C.	20 to 500° C.	300 to 500° C.	
		×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	Per cent
S866	Approximately 4 per cent silicon alloy	22.2	23.2	24.1	....	....	....	−0.01
S871	Approximately 7 per cent silicon alloy	21.8	22.8	23.5	....	....	....	+.00
S868	Approximately 10 per cent silicon alloy	21.1	21.9	22.9	....	....	....	+.00
S939	Normal 12.5 per cent silicon alloy, cast in green sand	19.4	21.5	24.8	24.8	24.7	24.5	+.11
		[1] 20.1	21.4	22.1	22.6	22.9	24.0	+.02
S940	Cut from same bar as S939	19.4	21.0	24.4	24.3	24.2	24.1	+.08
		[1] 22.2	22.1	22.8	23.2	23.2	23.8	+.03
S941	Modified 12.5 per cent silicon alloy	19.8	20.8	22.2	23.0	23.0	24.1	−.02
S942	Cut from same bar as S941	19.2	20.2	22.2	22.9	23.0	24.1	−.01

[1] Values on this horizontal line were obtained on a second heating.

The preceding table indicates that the coefficients of expansion generally decrease with increase in the silicon content. From 20 to 300° C. and higher temperatures or from 300 to 500° C., the coefficients of expansion of the normal 12.5 per cent silicon alloys are less in the second tests than in the first tests. For the range from 300 to 500° C. the rate of expansion in the second tests of these normal alloys is nearly equal to the rate of expansion of the modified alloys (in the first tests).

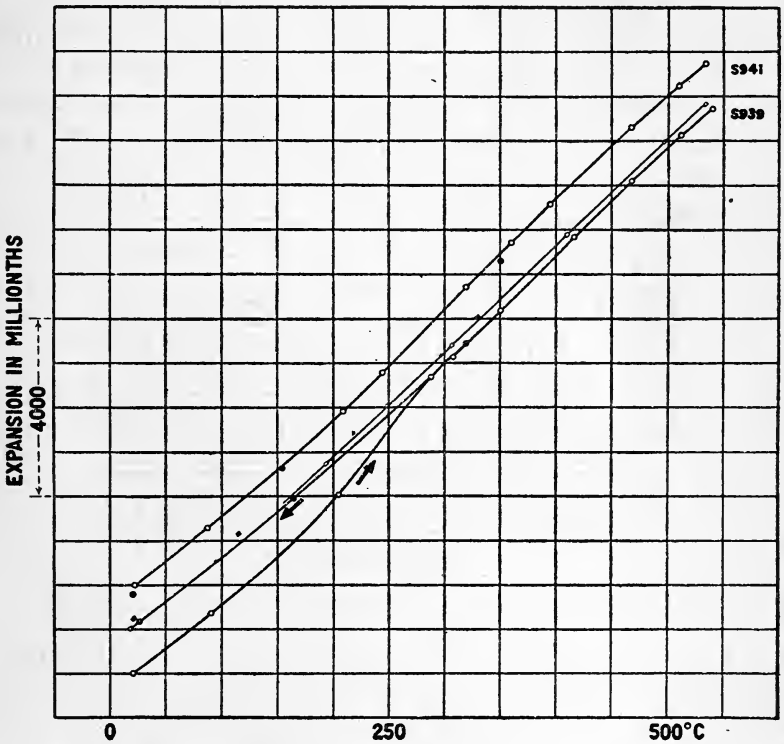

FIG. 10.—*Linear expansion of a normal and a modified aluminum-silicon alloy (12.5 per cent silicon)*

The observations on first tests are represented by circles and the observations on a second test by squares. The light symbols represent observations on heating and the dark symbols those on cooling.

In order to aid in the comparison of the results on expansion, the equilibrium diagram recently obtained by Edwards [13] is given in Figure 11 for aluminum-silicon alloys containing from 0 to 15 per cent silicon. He finds a normal eutectic at 11.6 per cent silicon, at about 577° C. Previous observers found that these alloys form a eutectiferous series with no chemical compounds. Fraenkel [14] states that the eutectic alloy contains about 90 per

[13] Edwards, Chem. and Met. Eng., 28, p. 165; 1923.

[14] Fraenkel, Z. anorg. Chem., 58, p. 154; 1908.

cent aluminum and 10 per cent silicon and freezes at about 576° C. Roberts [15] confirms Fraenkel's equilibrium diagram, but states that the eutectic temperature is about 578° C. Rosenhain, Archbutt, and Hanson [16] state that the eutectic contains 10.5 per cent of silicon and melts at 570° C., and that 1.5 per cent of silicon will dissolve in solid aluminum. Rassow [17] recently found a eutectic at about 13.8 per cent silicon.

Edwards states that the presence of a modifying agent will change the apparent eutectic composition and temperature in a very significant manner. "In general, a somewhat higher proportion of silicon can be used in the modified alloy than in the normal alloy. This is due to the fact that the process of modification raises the apparent eutectic composition considerably above its

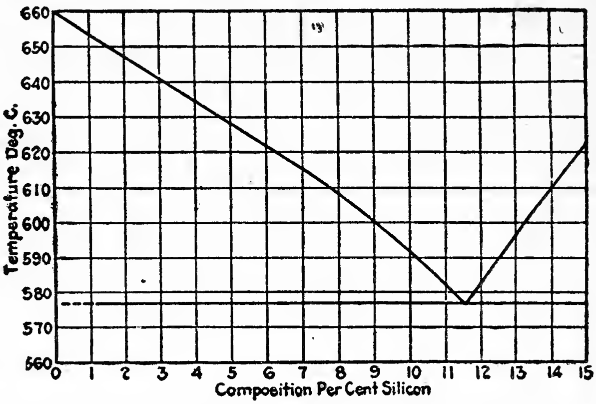

FIG. 11.—*Equilibrium diagram of aluminum-silicon alloys.* (*Edwards*)

normal figure (11.5 per cent silicon), and changes what would have been relatively large particles of excess silicon (in alloys containing over 11.5 per cent silicon) to very finely dispersed particles of eutectic silicon."[18] In a recent article on aluminum-silicon alloys, Jefferies [19] shows a number of typical micrographs of normal and modified alloys.

Figure 12 indicates the relations between the chemical composition and the average coefficients of expansion obtained on the first tests. As was noted before, the coefficients generally decrease with increase in the silicon content. There appears to be an exception in the case of the normal 12.5 per cent silicon

[15] Roberts, J. Chem. Soc., **105**, p. 1383; 1914.

[16] Rosenhain, Archbutt, and Hanson, Proc. Inst. Mech. Eng., p. 699, pt. 2; 1921.

[17] Rassow, Zeits. f. Metallkunde, p. 106, April, 1923.

[18] Edwards, Chem. and Met. Eng., **27**, p. 654; 1922.

[19] Jeffries, Chem. and Met. Eng., **26**, p. 750; 1922.

alloys for the temperature range between 20 and 300° C. However, on a second heating, the coefficients of these normal 12.5 per cent silicon alloys approached the lower values of the corresponding modified alloys, as may be seen from the preceding table.

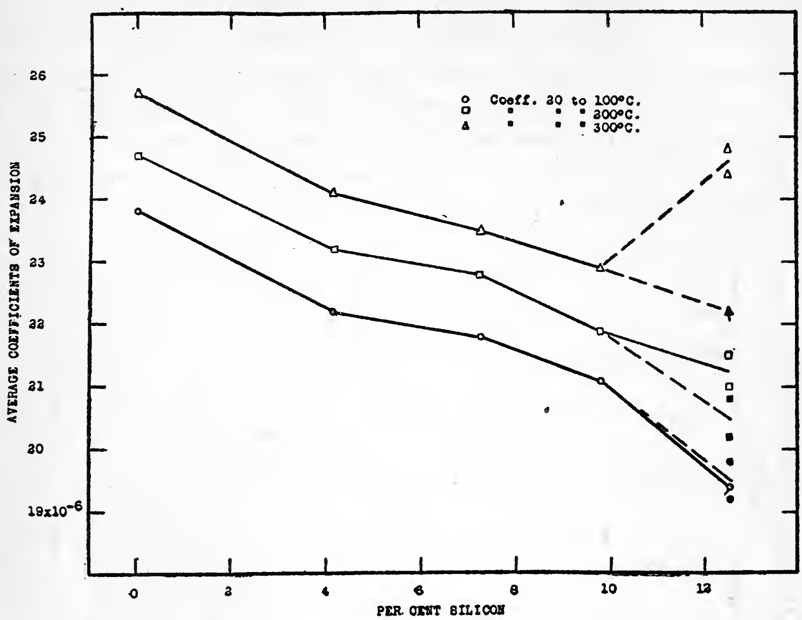

FIG. 12.—*Relations between coefficients of expansion and silicon content of aluminum-silicon alloys*

The light symbols represent values for normal alloys and the dark symbols for modified alloys. Where the values of two alloys are equal, a tagged symbol was employed as shown.

4. ALUMINUM-ZINC ALLOYS (SERIES 4)

Series 4 includes four samples of aluminum-zinc alloys containing approximately 12, 77, and 95 per cent zinc. The chemical analyses of these alloys are given in Table 13.

TABLE 13.—Chemical Analyses of Aluminum-Zinc Alloys

Laboratory number	Material	Chemical analysis					
		Aluminum	Zinc	Copper	Silicon	Iron	Manganese
		Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
S841[1]	Zinc alloy, rolled and drawn to hexagonal shape	[2] 85.83	12.17	1.47	0.21	0.31	0.01
S842	Cut from same bar as S841						
S389[3]	Approximately 77 per cent zinc alloy	22.57	[4] 77.22	.05	.05	.11	Nil.
S388[3]	Approximately 95 per cent zinc alloy	5.29	[4] 94.66	.02	.01	.02	Nil.

[1] Moderately high zinc rolling alloy sold mostly in the form of rod and wire.
[2] Aluminum by difference.
[3] Submitted by the metallurgical division of this bureau (chemical analysis by Aluminum Co. of America).
[4] Zinc by difference.

Expansion determinations were made on S841 from room temperature to about 530° C., and on S842 from room temperature to 300° C. The other two alloys were first examined from room temperature to 225° C., and then tests were repeated between room temperature and 300° C. All these alloys were tested in an oil bath except S841, which was tested in an electrically heated air furnace.

Figures 13 and 14 show the expansion curves of the alloys of this series. The expansion curves of the 12 per cent zinc alloys S841 and S842, indicate slight irregularities at about 200 and 240° C., respectively. The curves of the 77 per cent zinc and 95 per cent zinc alloys show very interesting results. At about 270° C.,

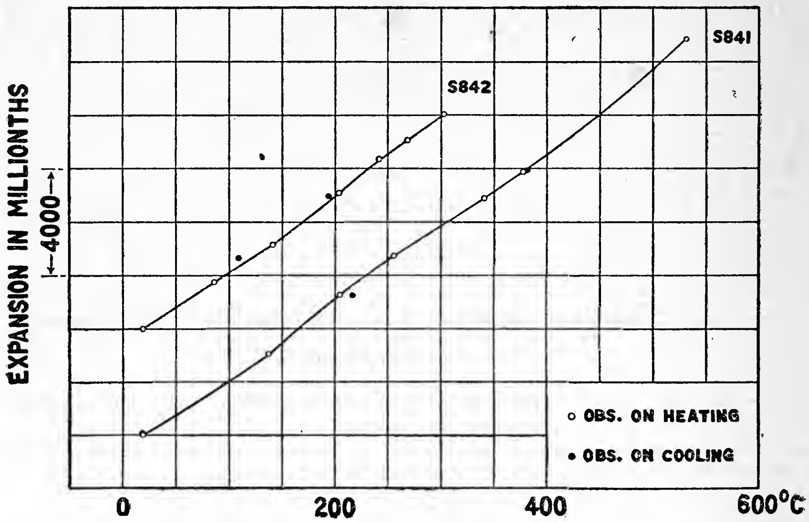

FIG. 13.—*Linear expansion of two samples cut from a bar of aluminum-zinc alloy (12 per cent zinc)*

these two high zinc alloys show transformations on heating. Between 270 and 282° C., the 77 per cent zinc alloy (S389) shows an anomalous expansion of 0.23 per cent and the 95 per cent zinc alloy (S388) shows a similar expansion of 0.15 per cent. On cooling, the latter alloy indicates an anomalous contraction at nearly constant temperature (about 150° C.).

In order to understand the results on the thermal expansion of these alloys, it will be necessary to refer to the equilibrium diagram of the aluminum-zinc alloys. The latest diagram [20] (and probably the best) is shown in Figure 15. *A B C D* is the liquidus and

[20] Hanson and Gayler, Journ. Inst. Metals, 27 (No. 1), p. 267; 1922.

A E B F G H D is the solidus. *B* is the eutectic point, and *K* (at about 79 per cent zinc) is the eutectoid point. The eutectoid line, *I K L*, occurs at 256° C., and extends toward the aluminum end of the diagram up to a composition of approximately 35 per cent zinc. *C G H* represents a reaction line. The various phases are indicated in the diagram. α represents a solid solution of aluminum in zinc, γ a solid solution of zinc in aluminum, and β

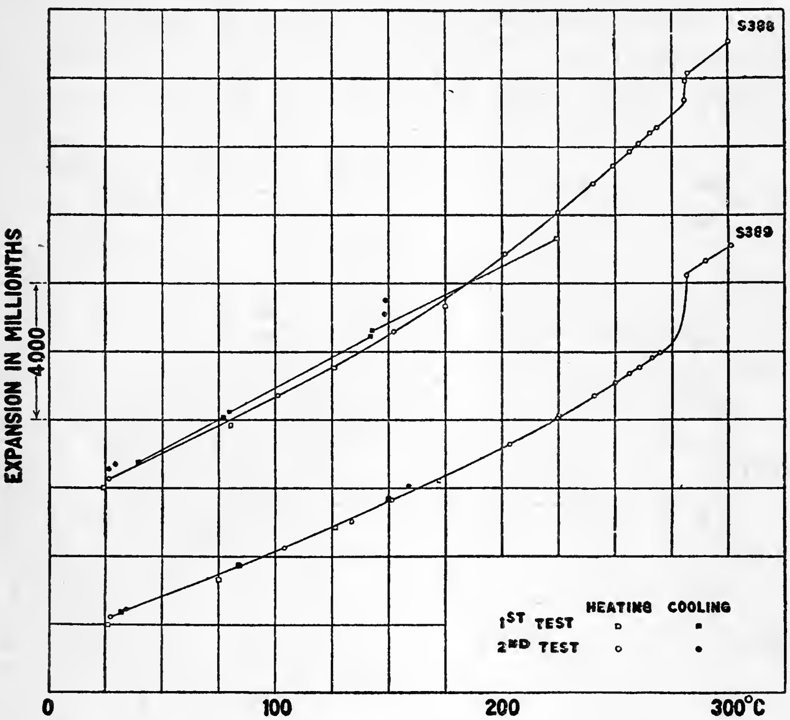

FIG. 14.—*Linear expansion of two aluminum-zinc alloys (containing 77 and 95 per cent zinc, respectively) showing transformations*

an intermediate solid solution. The actual constitution of the phase β is not known. Previous observers (Shepherd,[21] Rosenhain, and Archbutt,[22] and Bauer and Vogel [23]) indicated a chemical compound on their equilibrium diagrams. However, Hanson and Gayler state that no alloy composed of the β phase possesses the thermal properties associated with chemical compounds, and

[21] Shepherd, Jour. Phys. Chem., 9, p. 504; 1905.

[22] Rosenhain and Archbutt, Phil. Trans. Roy. Soc., 212, p. 315; 1912.

[23] Bauer and Vogel, Internat. Jour. of Metallography, 8, p. 101; 1916.

the existence of the compound Al_2Zn_3 is, therefore, definitely disproved.

The expansion curves of the 12 per cent zinc alloys (S841 and S842) show no transformations, for these alloys are solid solutions (γ) up to the melting point. According to the equilibrium diagram, zinc-aluminum alloys containing from 0 to about 35 per cent zinc (γ or $\gamma+$ some eutectoid) have no transformations up to the melting points. Smirnoff and Schulze found that no transformations occurred in alloys containing less than 30 or 35 per cent zinc.

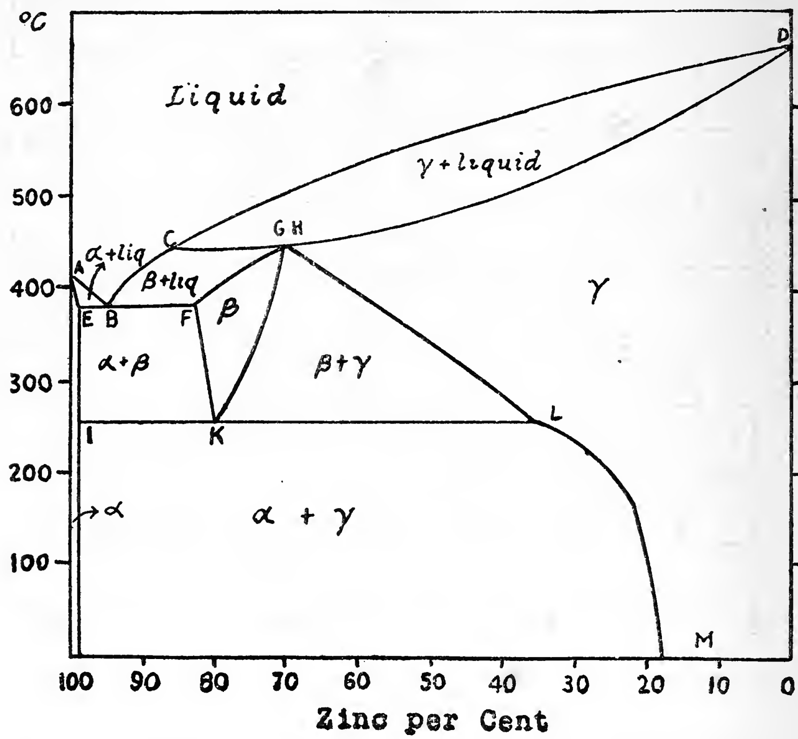

FIG. 15.—*Equilibrium diagram of aluminum-zinc alloys. (Hanson and Gayler)*

The 77 per cent zinc alloy (S839) consists essentially of a eutectoid mixture ($\alpha+\gamma$), and the 95 per cent zinc alloy (S388) consists of α and eutectoid ($\alpha+\gamma$). Both alloys indicated marked changes in expansion between 270 and 280° C., due to formation of β. According to the equilibrium diagram, aluminum-zinc alloys containing from about 35 to 99 per cent zinc have transformations at 256° C., which is in close agreement with the present results and those of Smirnoff and Schulze. From an

examination of the results of Smirnoff, Schulze, and the present author it is evident that the alloy of eutectoid composition (approximate) shows the greatest change in expansion at the transformation temperature, and that in alloys containing from about 35 to 99 per cent zinc this change decreases with decrease in the amount of eutectoid contained.

The average coefficients of expansion given in Table 14 were computed from the expansion curves of the four alloys. The changes in length after the expansion tests from the lengths before these tests are included in this table. The plus (+) sign denotes an increase in length and the minus (−) sign a decrease in length.

TABLE 14.—Average Coefficients of Expansion and Length Changes of Aluminum-Zinc Alloys

Laboratory number	Material	Average coefficients of expansion per degree centigrade						Changes in length due to heat treatment received during test
		20 to 100° C.	20 to 200° C.	20 to 250° C.	20 to 300° C.	20 to 400° C.	20 to 500° C.	
S841 [1]	Approximately 12 per cent zinc alloy, rolled and drawn to hexagonal shape	$\times 10^{-6}$ 24.3	$\times 10^{-6}$ 28.1	$\times 10^{-6}$ 28.3	$\times 10^{-6}$ 27.9	$\times 10^{-6}$ 27.6	$\times 10^{-6}$ 28.6	Per cent +0.01
S842	Cut from same bar as S841	25.5	27.3	28.5	28.3	....	....	....
S389	Approximately 77 per cent zinc alloy	27.5	29.6	....	....	....	....	+.02
		[2] 26.0	28.3	30.5	....	....	....	−.01
S388	Approximately 95 per cent zinc alloy	33.3	35.7	....	....	....	....	+.02
		[2] 32.0	37.2	40.7	....	....	....	+.02

[1] Contains also 1.47 per cent copper.
[2] Values given on this horizontal line were obtained on a second heating.

The following figure gives a comparison of the coefficients of expansion obtained by Smirnoff, Schulze, and the present author, and the relation of these results to the equilibrium diagram. The coefficient of expansion of cast zinc (99.99 per cent), 39.5×10^{-6} between 20 and 250° C., which was recently obtained by the writer, is included. There are discrepancies in some of the results, evidently due to impurities and different heat treatments. The eutectic alloy has the largest coefficient of expansion from room temperature to 250°C., and according to Smirnoff the eutectoid alloy appears to have the lowest coefficient of expansion.

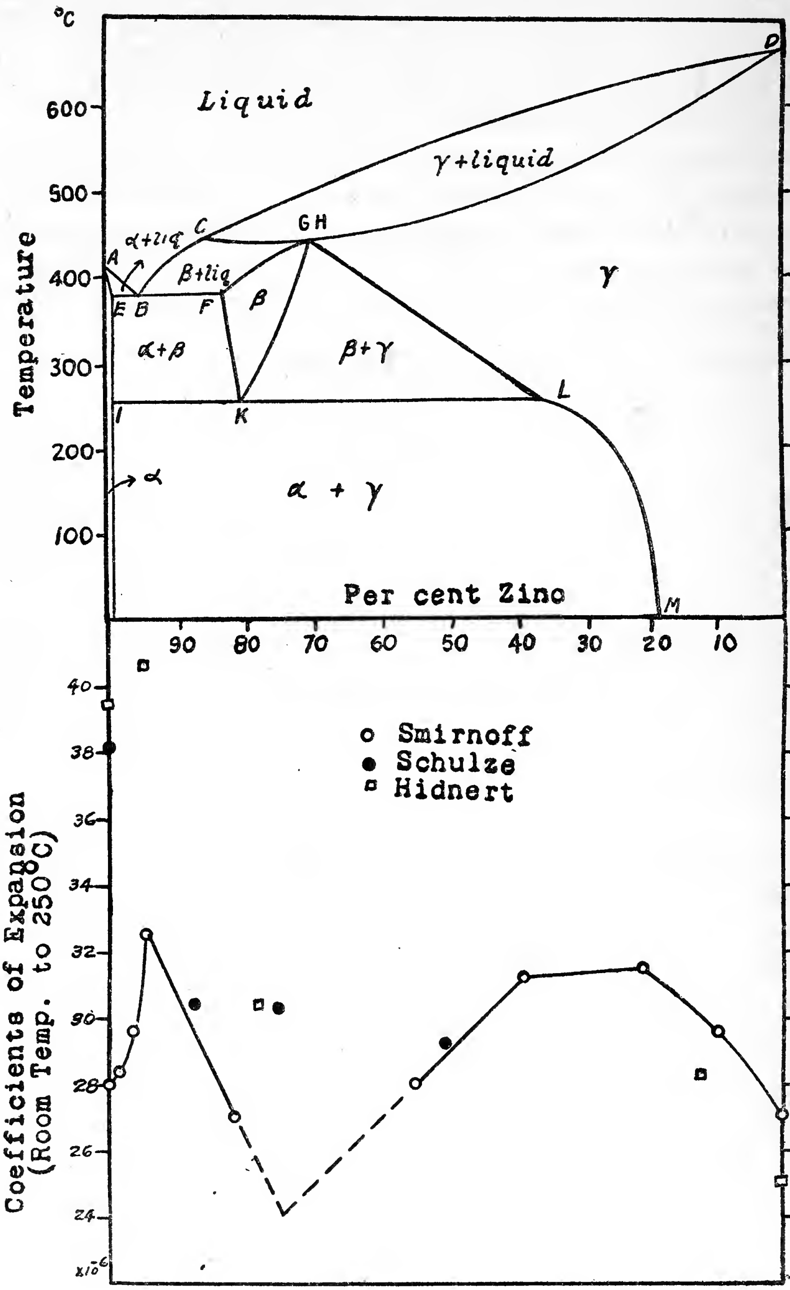

FIG. 16.—*Comparison of coefficients of expansion of aluminum-zinc alloys and their relation to the equilibrium diagram*

5.—ALUMINUM-MANGANESE AND ALUMINUM-MANGANESE-COPPER ALLOYS (SERIES 5)

In this series there are four samples of aluminum-manganese alloys and two samples of aluminum-manganese-copper alloys. The chemical compositions and the average coefficients of expansion for various temperature ranges are given in the following table:

TABLE 15.—Chemical Compositions and Average Coefficients of Expansion of Aluminum-Manganese and Aluminum-Manganese-Copper Alloys

Laboratory number	Material	Composition					Average coefficients of expansion per degree centigrade						
		Al[1]	Mn	Cu	Si	Fe	20 to 100° C.	20 to 200° C.	20 to 250° C.	20 to 300° C.	20 to 400° C.	20 to 500° C.	20 to 600° C.
		Per cent	Per cent	Per cent	Per cent	Per cent	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$
S845 [2]	3 S sheet, rolled to one-fourth inch	97.78	1.05	0.19	0.41	0.57	23.8	25.7	26.1	25.9	26.5	27.5	28.6
S846	Duplicate of S845	......	......	......	......	......	23.7	25.6	25.9	25.5	26.1	27.4	28.4
S837	Manganese alloy, sand cast	96.73	1.80	.23	.40	.84	23.1	24.2	24.7	25.5	25.9	27.0	27.9
S838	Cut from same bar as S837	......	......	......	......	......	23.1	24.4	25.2	25.8	26.4	27.5	......
S839 [3]	Manganese, copper (McKinney) alloy, sand cast	96.20	1.08	1.91	.30	.51	23.6	25.2	26.7	26.9	26.8	27.5	......
S840 [4]	Cut from same bar as S839	......	......	......	......	......	23.7	24.2	25.7	26.8	......	......	......

[1] Per cent aluminum determined by difference.
[2] Brinell hardness No. 56.
[3] Used at the Washington Navy Yard to a considerable extent.
[4] Sample tested to 300° C. in an oil bath. All other samples of this series were heated in an air furnace.

From a comparison of these results with those obtained on commercial aluminum (Table 8), it is evident that the addition of 1 or 2 per cent manganese (or 1 per cent manganese and 2 per cent copper) to commercial aluminum, causes a decrease in the coefficients of expansion. The coefficients of expansion of the samples of aluminum-manganese alloys containing about 2 per cent manganese are generally less than those containing 1 per cent manganese.

In nearly all cases, the observations on cooling lie above the expansion curves on heating, and, therefore, at the end of the expansion tests, the samples were longer than before these tests. The average increase in length was 0.04 per cent.

6. ALUMINUM-SILICON-COPPER AND ALUMINUM-SILICON-COPPER-MANGANESE ALLOYS (SERIES 6)

Series 6 includes eight alloys lying near the aluminum corner of the ternary system—aluminum-silicon-copper; and four aluminum-rich alloys of the quaternary system—aluminum-silicon-copper-manganese. The engineering division, Air Service, of the War Department, McCook Field, Dayton, Ohio, furnished these alloys which were sand cast.

Before the expansion tests, the alloys were heated to 400° C. and allowed to cool in an electric furnace. Expansion tests were then

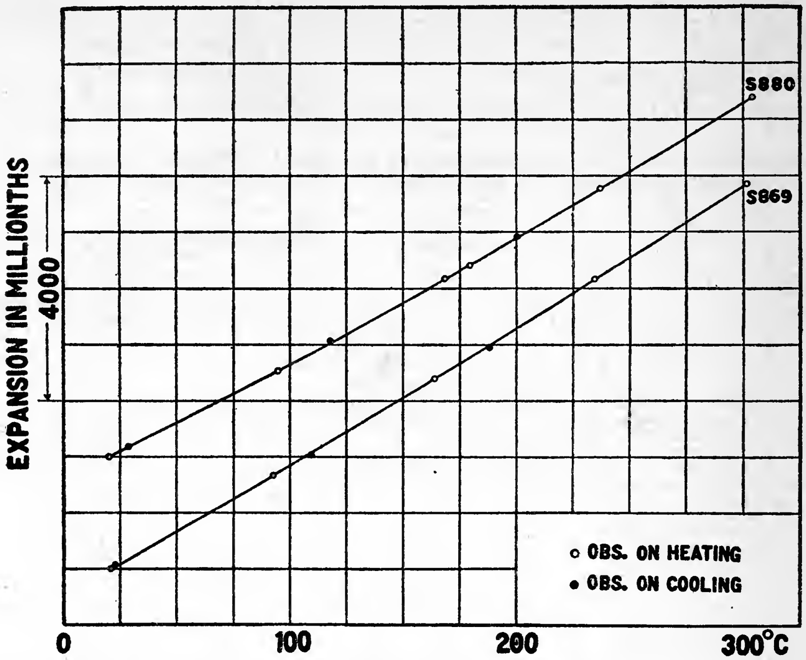

FIG. 17.—*Linear expansion of an aluminum-silicon-copper alloy (S869) and an aluminum-silicon-copper-manganese alloy (S880)*

made on these samples from room temperature to 300° C., in an oil bath. The chemical compositions and the average coefficients of expansion for various temperature ranges are given in Table 16.

TABLE 16.—Chemical Compositions and Average Coefficients of Expansion of Aluminum-Silicon-Copper and Aluminum-Silicon-Copper-Manganese Alloys

Laboratory number	Chemical composition [1]					Average coefficients of expansion per degree centigrade			
	Al [2]	Si	Cu	Fe	Mn	20 to 100° C.	20 to 200° C.	20 to 250° C.	20 to 300° C.
	Per cent	Per cent	Per cent	Per cent	Per cent	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$
S869	93.91	3.33	2.2	0.55	0.01	23.4	23.9	24.2	24.4
S867	89.62	7.42	2.43	.53	Nil.	21.7	22.5	23.0	23.4
S870	87.11	9.96	2.33	.60	Nil.	20.7	21.7	22.2	22.7
S872	91.27	3.75	4.41	.57	Nil.	22.4	23.4	23.8	24.1
S873	88.29	6.61	4.53	.57	Nil.	{21.4 21.5	22.5 22.3	23.1 22.8	(3) 23.1
S876	84.60	10.28	4.58	.54	Nil.	20.4	21.3	21.8	22.1
S875	88.66	4.08	6.62	.64	Nil.	21.8	22.9	23.4	23.6
S877	83.73	9.45	6.29	.53	Nil.	20.6	21.6	22.0	22.2
S878	93.00	3.12	2.4	.55	.93	22.2	23.4	23.7	23.8
S880	86.39	9.97	2.32	.50	.82	20.4	21.5	22.0	22.4
S879	85.84	10.22	2.49	.56	.89	20.8	21.5	22.0	22.3
S874	85.48	10.18	2.47	.70	1.17	20.4	21.5	22.0	22.3

[1] Chemical analyses made by Aluminum Co. of America on all samples of this series except S869 and S878, which were analyzed by J. A. Scherrer, of this bureau.
[2] Aluminum by difference.
[3] Observation wire broke at about 300° C. The results obtained on a repeated test are given in the next line.

Figure 17 shows two typical expansion curves of this series—one for a ternary alloy (S869) and another for a quaternary alloy (S880). The curves of this series are regular, and the observations on cooling closely follow the expansion curves on heating. At the end of the tests, the samples indicated no appreciable changes in length from the original lengths.

The curves on the accompanying triangular diagram (fig. 18) were derived from the data given in the preceding table and in series 1, 2, and 3. These curves indicate the average coefficients

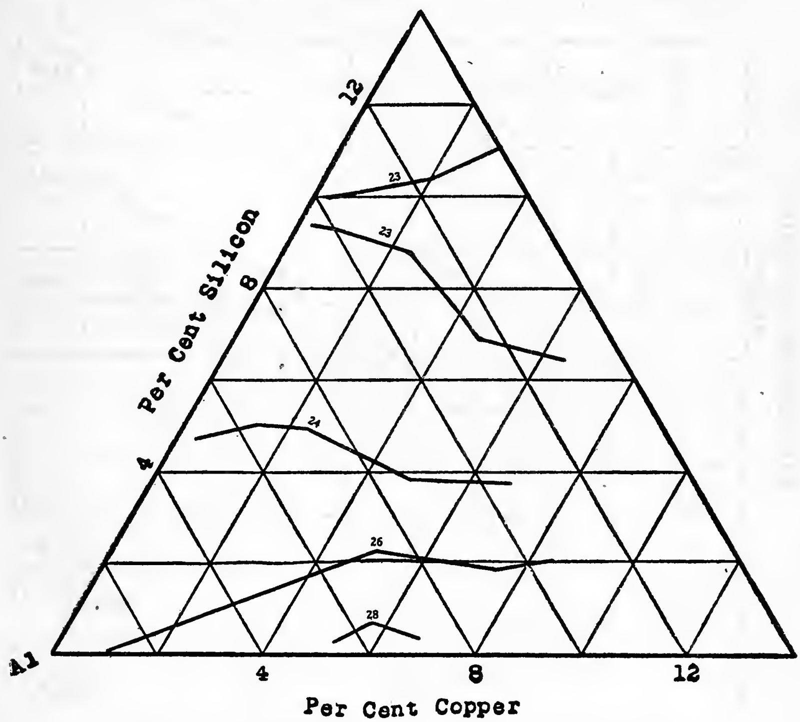

FIG. 18.—*Portion of triangular diagram indicating the effect of composition on the coefficient of expansion (in millionths per degree C.) of aluminum-rich ternary alloys between 20 and 300° C.*

of expansion from 20 to 300° C. for various aluminum-rich alloys (binary and ternary). The diagram gives a general idea of the effect of change of composition on the coefficient of expansion.

In nearly every case the coefficients of expansion decrease with increase in the silicon content. In general, the substitution of approximately 1 per cent manganese for a corresponding amount of aluminum in aluminum-silicon-copper alloys containing from 87 to 94 per cent aluminum. causes a decrease in the coefficients of expansion.

7. DURALUMIN (SERIES 7)

The first tests at this bureau on the thermal expansion of duralumin were made[24] in 1911. Three samples having an average density of 2.78 g/cm³ and an ultimate strength of 52,200 lb./in.², were prepared by Vickers, Sons & Maxium Co., of England. Between 0 and 30° C. the average coefficients of expansion of these samples were found to vary from 22.4×10^{-6} to 22.8×10^{-6} per degree centigrade.

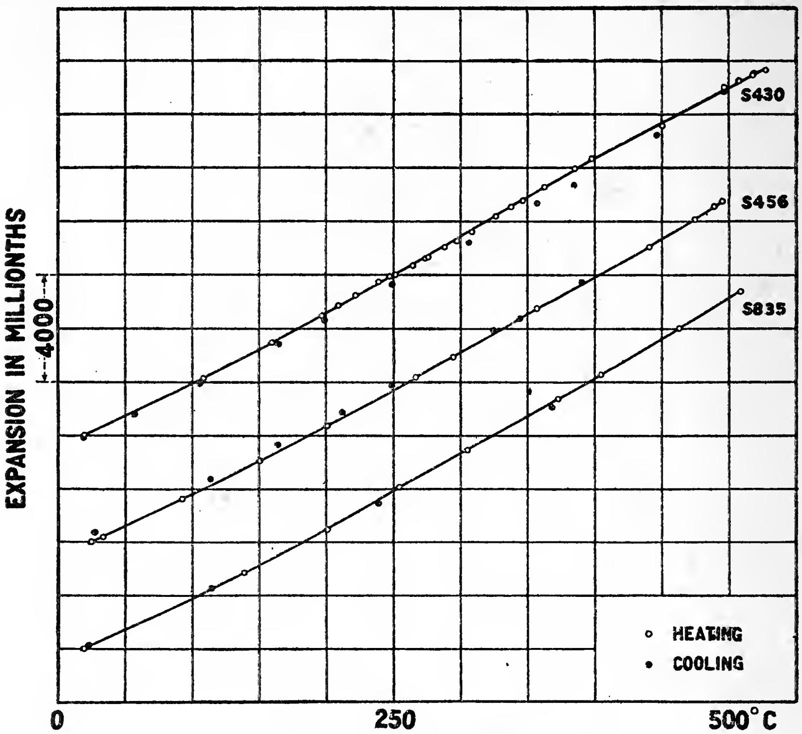

FIG. 19.—*Linear expansion of three samples of duralumin.*

S835 Sand cast. S456 Hot rolled. S430 Quenched from 520° C. and aged two days at 120° C.

In the present investigation, eight samples of duralumin were examined. The chemical compositions and the average coefficients of expansion of these alloys of the aluminum-copper-magnesium series are given in Table 17. This table also indicates the length changes after the expansion tests. The plus (+) sign signifies an increase in length, and the minus (−) sign a decrease in length.

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[24] By A. W. Gray, formerly of this bureau.

TABLE 17.—Chemical Compositions, Average Coefficients of Expansion, and Length Changes of Duralumin

Laboratory number	Material	Composition					
		Al[1]	Cu	Mg	Mn	Fe	Si
		Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.
S835	Duralumin, sand cast	94.79	3.68	0.36	0.57	0.35	0.25
S836	Cut from same bar as S835	....	....	....	....	....	....
S456	Duralumin, hot rolled[2]	94.36	3.74	1.08	....	.52	.30
S430	Duplicate of S456 cold rolled to 0.09 inch and heat treated[3]	....	....	....	....	....	....
S935[4]	Duralumin, hard rolled	94.58	3.66	.52	.51	.37	.16
S936	Duplicate of S935	....	....	....	....	....	....
S937	Duplicate of S935, heat treated[6]	....	....	....	....	....	....
S938	Duplicate of S937	....	....	....	....	....	....

Laboratory number	Material	Average coefficients of expansion per degree centigrade						Changes in length due to heat treatment received during test
		20 to 100° C.	20 to 200° C.	20 to 250° C.	20 to 300° C.	20 to 400° C.	20 to 500° C.	
		$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	$\times10^{-6}$	Per cent
S835	Duralumin, sand cast	23.6	24.6	25.7	26.0	26.7	27.3	+0.01
S836	Cut from same bar as S835	23.2	24.8	25.8	26.0	26.8	27.6	+.03
S456	Duralumin, hot rolled[2]	23.8	24.7	25.3	25.7	26.3	27.2	+.03
S430	Duplicate of S456 cold rolled to 0.09 inch and heat treated[3]	23.7	25.2	25.8	26.4	27.3	27.3	−.01
S935[4]	Duralumin, hard rolled	23.1	26.0	26.5	26.7	....	....	+.06
		[5] 22.5	24.6	24.8	25.3	26.2	26.1	+.03
S936	Duplicate of S935	23.1	26.0	26.7	26.9	....	....	+.06
		[5] 22.2	23.5	24.1	24.7	25.7	25.4	+.01
S937	Duplicate of S935, heat treated[6]	23.2	24.0	25.3	25.9	....	....	+.03
		[5] 21.9	22.9	23.7	24.7	25.7	26.4	+.04
S938	Duplicate of S937	23.2	24.2	25.4	26.2	....	....	+.04
		[5] 22.6	24.1	24.9	25.6	26.6	26.9	+.06

[1] Aluminum determined by difference.
[2] Rolled at about 410° C. from 3½ inches to one-fourth inch thick.
[3] Quenched in water from 520° C., and aged two days at 120° C.
[4] Contains also 0.20 per cent calcium.
[5] Values given on this horizontal line were obtained on a second heating.
[6] Tempered by heating for a short time at about 500° C., and quenching.

Samples S935 to S938, inclusive, were first examined from room temperature to 300° C. in an oil bath, and then tests were repeated between room temperature and 500° C. in an electric furnace. The coefficients of expansion on the second tests are less than those obtained on the first tests. For the heat-treated alloys (S937 and S938), the difference between the coefficients of the first and second tests is generally less than in the hard-rolled alloys (S935 and S936).

Figures 19 and 20 show expansion curves of duralumin in various conditions. The curves of samples S430, S935, and S936 indicate irregularities at about 400° C.

8. "VERILITE" (SERIES 8)

This final group includes two samples of cast "Verilite," submitted by the division of structural engineering of this bureau. The chemical composition of these specimens is as follows: Aluminum, 95.5 per cent; nickel, 1.5 per cent; copper, 1.0 per cent; chromium, 1.5 per cent; and manganese, 0.5 per cent.

Expansion tests were made in an oil bath from room temperature to 300° C. The observations are represented graphic-

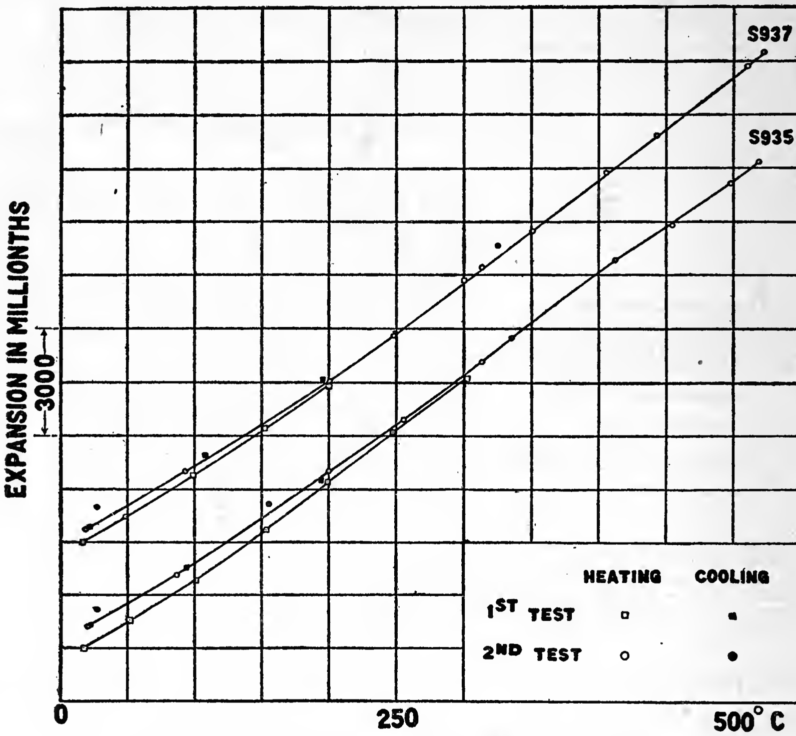

FIG. 20.—*Linear expansion of two samples of duralumin*

S935 Hard rolled. S937 Tempered by heating to 500° C. and quenching.

ally in Figure 21. The expansion curves are regular and may be represented by the following second-degree equation:

$$L_t = L_o \left[1 + (21.05\, t + 0.01473\, t^2)\, 10^{-6}\right]$$

where L_t is the length at any temperature t between 14 and 302° C., and L_o the length at 0° C. The length at any temperature t as determined from this equation is accurate to ± 0.000015 per unit length.

The observations on cooling lie above the expansion curves on heating. At the end of these tests, the specimens were found to be 0.03 per cent longer than before the tests.

TABLE 18.—Average Coefficients of Expansion of "Verilite"

Laboratory number	Average coefficients of expansion per degree centigrade			
	20 to 100° C.	20 to 200° C.	20 to 250° C.	20 to 300° C.
	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$
S425	23.2	24.2	25.0	25.8
S426	23.3	24.2	25.0	25.8

Table 18 gives the average coefficients of expansion for several temperature ranges. These values were derived from the expansion curves on heating.

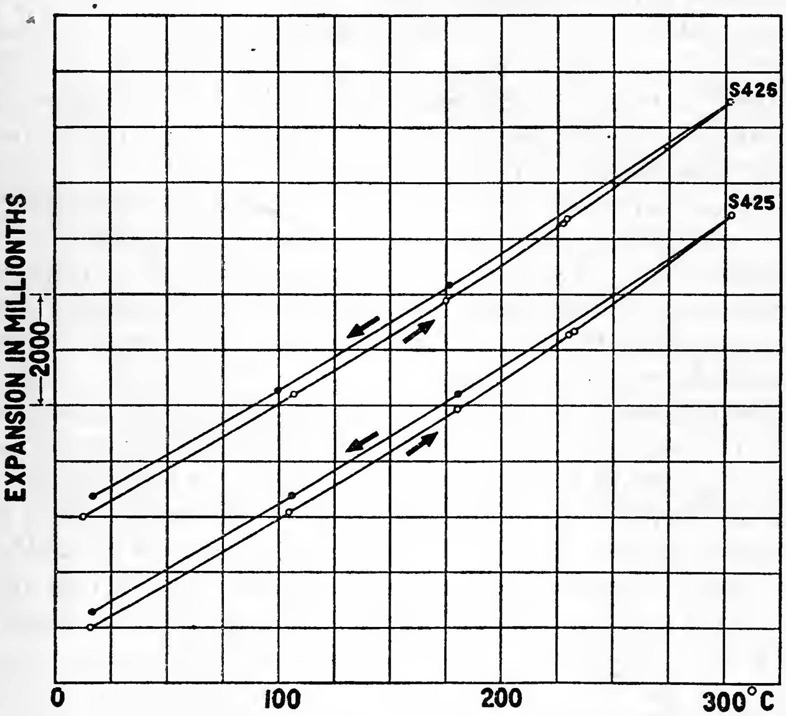

FIG. 21.—*Linear expansion of two samples of "Verilite"*

VI. SUMMARY

This paper gives data on the thermal expansion of 4 samples of aluminum and 51 samples of important aluminum alloys. The preparation, chemical composition, heat treatment, etc., are included. Most of the specimens were examined from room temperature to about 500° C. Typical expansion curves of the various groups of samples are shown and discussed. In some cases, the data on expansion were compared with the equilibrium

diagrams of binary alloys. After the expansion tests, the changes in length from the original lengths were determined.

A description of the apparatus used in this research, and a review of available information obtained by previous observers on the thermal expansion of aluminum and some of its alloys, are given.

The following average equation

$$L_t = L_0 \, [1 + (22.58 \, t + 0.00989 \, t^2) \, 10^{-6}]$$

is given as the most probable second degree equation for the expansion of cast aluminum (99.95 per cent) from room temperature to about 610° C. For the aluminum-copper alloys containing from 4 to 12 per cent copper, a figure is given which shows the relations between the chemical composition and the coefficients of expansion for various temperature ranges. The curves indicate maxima at 6 or 8 per cent copper.

The coefficients of expansion of aluminum-silicon alloys (4 to 12.5 per cent silicon) generally decrease with increase in the silicon content. Two normal 12.5 per cent silicon alloys exhibited certain peculiarities which were discussed. Duplicates of these alloys modified by the addition of 0.1 per cent metallic sodium did not show these phenomena.

The expansion curves of two aluminum-zinc alloys containing 77 and 95 per cent zinc, respectively, indicated anomalous expansions at constant temperature (about 270° C. on heating), due to a transformation by the formation of β constituent. From the results of previous observers and the present research it is evident that the alloy of eutectoid composition (about 79 per cent zinc) shows the greatest change in expansion at the transformation or eutectoid temperature, and that in alloys containing from about 35 to 99 per cent zinc this anomalous change decreases with decrease in the amount of eutectoid contained.

The addition of 1 or 2 per cent manganese (or 1 per cent manganese and 2 per cent copper) to commercial aluminum caused a decrease in the coefficients of expansion. The coefficients of expansion of the samples of aluminum-manganese alloys containing about 2 per cent manganese are generally less than those containing 1 per cent manganese.

A triangular diagram is shown which indicates the effect of change of composition on the coefficients of expansion of aluminum-silicon-copper alloys lying near the aluminum corner of the

ternary system. For the aluminum-silicon-copper and aluminum-silicon-copper-manganese alloys investigated (containing from 84 to 94 per cent aluminum) the coefficients of expansion decrease with increase in the silicon content. In general, the substitution of approximately 1 per cent manganese for a corresponding amount of aluminum in aluminum-silicon-copper alloys containing from 87 to 94 per cent aluminum caused a decrease in the coefficients of expansion.

The coefficients of expansion of a number of samples of duralumin in various conditions were derived. In hard-rolled alloys and duplicates that were heat treated the coefficients on second tests are less than those obtained on the first tests. For the heat-treated alloys the difference between the coefficients of the first and second tests is generally less than in the hard-rolled alloys.

The thermal expansion of cast "Verilite" (Al 95.5, Ni 1.5, Cu 1.0, Cr 1.5, Mn 0.5) between 14 and 302° C. is represented by the following empirical equation:

$$L_t = L_o[1 + (21.05\ t + 0.01473\ t^2)\ 10^{-6}]$$

In conclusion, a comparison of the average coefficients of expansion of the materials investigated are given for several temperature ranges in the following table. For values of individual samples over various temperature ranges (between 20 and 500° C.) reference should be made to the proper sections of the paper.

TABLE 19.—Average Coefficients of Expansion of Aluminum and Various Aluminum Alloys

Series	Aluminum content	Average coefficients of expansion per degree centigrade		
		20 to 100° C.	20 to 200° C.	20 to 300° C.
	Per cent	×10⁻⁶	×10⁻⁶	×10⁻⁶
1. Aluminum (a) Pure aluminum	99.95	23.8	24.7	25.7
1. Aluminum (b) Commercial aluminum	99.15	23.9	25.9	26.7
2. Aluminum-copper alloys	87 to 95	22.2 to 24.6	23.6 to 26.8	26.4 to 29.2
3. Aluminum-silicon alloys	87 to 95	19.2 to 22.2	20.2 to 23.2	22.2 to 24.8
4. Aluminum-zinc alloys	5 to 86	24.3 to 33.3	27.3 to 37.2	28.3 to [1] 40.7
5. Aluminum-manganese and aluminum-manganese-copper alloys	96 to 98	23.1 to 23.8	24.2 to 25.7	25.5 to 26.9
6. Aluminum-silicon-copper and aluminum-silicon-copper-manganese alloys	84 to 94	20.4 to 23.4	21.3 to 23.9	22.1 to 24.4
7. Duralumin	94 to 95	21.9 to 23.8	22.9 to 26.0	24.7 to 26.9
8. Verilite	95.5	23.2	24.2	25.0

[1] From 20 to 250° C.

WASHINGTON, July 9, 1924.